

Received: 01 February 2025 • Revised: 14 April 2025 • Accepted: 16 May 2025

Research

doi: 10.22034/jcema.2025.541044.1163

Seismic Performance Assessment of Reinforced Concrete Moment-Resisting Frames with Shear Walls Reinforced by Shape Memory Alloy Bars

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ABSTRACT

Shape Memory Alloy (SMA) reinforcing bars, due to their unique self-centering capability and high energy dissipation, can significantly enhance the seismic performance of structures located in high-seismic-risk regions. In reinforced concrete (RC) buildings, the combined use of Special Moment-Resisting Frames (SMRF) and Reinforced Concrete Shear Walls is a common lateral load-resisting system. Although the inherent ductility of SMRFs improves their seismic response, the influence of integrating SMA reinforcement within structural elements of such systems has not yet been comprehensively investigated. In this study, a 12-story RC building located in a very high seismic hazard zone, consisting of an SMRF and RC shear walls, was modeled and analyzed in three different cases using various types of SMA reinforcing bars. The results indicated that the inclusion of SMA reinforcement led to an average reduction in total building weight by approximately 0.13%, a decrease in support moments by about 10.22%, and a reduction in peak interstory drift by nearly 10.42% compared to the reference model without SMA bars. These findings highlight the high efficiency of SMA reinforcement in enhancing seismic performance and reducing the vulnerability of RC structures.

Keywords: Shape Memory Alloy (SMA), Special Moment-Resisting Frame, Reinforced Concrete Shear Wall, Seismic Performance

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1. INTRODUCTION

Iran is located in one of the most seismically active regions of the world, characterized by a dense network of active faults that continuously pose the risk of strong earthquakes. The characteristics of seismic events, including amplitude, duration, and frequency content, can

vary significantly depending on site conditions and geotechnical properties. These uncertainties make improving the seismic resilience of reinforced concrete (RC) structures a critical research priority. Previous studies have investigated the application of Shape Memory Alloy (SMA) rebars in RC

structural components such as beam-column joints, shear walls, and flexural members, demonstrating their potential to enhance ductility, reduce residual deformations, and improve post-earthquake functionality. However, most existing research has been limited to isolated members or simplified structural models, without addressing the integrated performance of realistic building systems under seismic loading. The novelty of this study lies in shifting the focus from component-level analysis to a full structural system perspective. Specifically, we conduct a comprehensive seismic performance assessment of RC moment-resisting frames with shear walls reinforced by SMA bars. Unlike prior works, this research evaluates system-level effects—including weight reduction, base shear demand, displacement response, and energy dissipation. In a realistic 12-story RC building located in a high seismic hazard zone. By bridging the gap between member-scale investigations and system-scale applications, this study provides new insights into the feasibility of implementing SMA reinforcement in practical RC building design, offering guidance for both researchers and engineers

The application of Shape Memory Alloys (SMA) in reinforced concrete (RC) structures has been widely studied, ranging from element-level investigations to system-level seismic performance assessments. Existing studies can broadly be grouped into three main categories. Experimental and numerical studies have demonstrated the localized benefits of SMA reinforcement in beams and joints. For example, Cu–Al–Mn SMA bars placed away from beam ends improved stiffness and energy dissipation [1]. Alam et al. [2] developed predictive models for moment–curvature and load–displacement relationships in SMA-reinforced beam–columns, while Nahar et al. [3] confirmed the superior self-centering capacity of SMA-based joints compared to conventional steel, while numerical fragility analyses revealed that SMA-reinforced joints exhibited 20–30% higher collapse margin ratios in terms of peak interstory drift and up to 60% higher ratios for residual drift. Overall, SMA reinforcement improves ductility and residual drift control at the member level, but most applications remain confined to isolated elements rather than system-wide implementations. Overall, these studies agree that SMA reinforcement improves ductility and residual drift control, yet

they remain confined to isolated member-level applications, limiting insights into system-wide behavior. At the frame level, nonlinear analyses by Montasir et al. [4] demonstrated significant increases in collapse capacity for three- to eight-story buildings, with Collapse Margin Ratios (CMR) enhanced relative to conventional steel frames. Youssef et al. [5] further showed that conventional RC frames dissipate seismic energy through yielding, which leaves significant residual drifts and compromises serviceability. By incorporating SE-SMA bars and considering both horizontal and vertical seismic excitations, optimal SMA placement was identified in a six-story RC building, demonstrating substantial mitigation of residual deformations. Similarly, Ghasemi et al. [6] examined 3-, 6-, and 8-story five-bay frames under mainshock and aftershock sequences, showing that embedding SMA bars in plastic hinge regions alongside ultra-high-performance steel-fiber-reinforced concrete (UHPSFRC) synergistically reduced transient and residual interstory drifts. Bonet et al. [7] extended this approach by designing twelve RC frames with high-performance concrete and SMA bars in critical sections, showing improved base shear, reduced residual displacements, and increased response modification factors. Abulfath [8] emphasized that SMA-equipped frames provide enhanced lateral stiffness, energy dissipation, and ductility, although base shear demands increase for a given ductility level. Collectively, these studies confirm the feasibility of SMA reinforcement in multistory frames. However, most analyses employ simplified or symmetric frame models, and relatively few address the influence of wall–frame interaction or vertical ground motion effects. Although such studies illustrate the feasibility of SMA for multi-story structures, they typically employ symmetric or simplified frame models, without considering more complex structural layouts or the influence of wall–frame interaction. The unique superelastic properties of SMA rebars have also encouraged their application in shear walls. Although RC shear walls offer high stiffness and strength, post-earthquake reports highlight difficulties in repairing residual displacements and rotations. Recent investigations propose using superelastic, self-centering SMA rebars to address these issues [9]. De Almeida et al. [10] experimentally confirmed that NiTi SMA-reinforced walls exhibited

significant reductions in residual displacements while maintaining energy dissipation capacity. Abrik et al. [11-13] performed analytical fragility assessments of 10- and 20-story SMA-reinforced shear walls, reporting enhanced self-centering capacity and reduced seismic fragility compared to conventional RC walls. Cruz-Noguez et al. [14] experimentally compared slender RC shear walls reinforced with SMA, FRCC, and GFRP bars against conventional steel walls. Their results showed that SMA-reinforced walls developed longer plastic hinge lengths, reduced residual displacements, and demonstrated improved self-centering capacity. Three self-centering performance targets were also proposed to guide seismic design of innovative wall systems. Together, these contributions highlight the potential of SMA in wall-dominated systems, both for new construction and retrofitting. Yet most investigations remain limited to component-scale tests or single-wall simulations, without considering full building-system interaction. Another research has focused on SMA reinforcement in shear walls. De Almeida et al. [10] observed reduced residual displacements in NiTi-reinforced walls, while Abrik et al. [15] confirmed enhanced self-centering and reduced fragility in SMA-based shear walls. These contributions highlight the potential of SMA in wall-dominated systems, yet most investigations remain limited to component-scale experiments or single-wall simulations, rather than integrated building systems. Soufianopoulos et al. [16] investigated the seismic enhancement of single-story, single-bay STMFs by incorporating SMA elements into the special segment. Traditionally, STMFs dissipate seismic energy through plastic hinges at chord corners. In the proposed system, this mechanism was replaced by the superelastic response of SMA elements. Nonlinear time-history analyses in SeismoStruct showed that SMA-integrated STMFs experienced notable reductions in peak displacements, enabling the possibility of lighter yet resilient structural systems. Although the effect of earthquake duration on liquefaction and structural stability is well known, its influence on seismic response is less studied. Requonandan et al. [17] demonstrated through incremental dynamic analyses that longer-duration ground motions

increase collapse risk for non-ductile RC frames, emphasizing the need to account for duration in seismic design alongside intensity and frequency content. Ghasemi et al. [6] showed synergistic effects of SMA and UHPSFRC in reducing interstory drifts in 3-, 6-, and 8-story frames under mainshock–aftershock sequences. Esfahani et al. [18] proposed reinforcing circular RC columns with SMA and GFRP bars, demonstrating improved lateral capacity, energy dissipation, reduced residual displacement, and increased ductility. Youssef et al. [19] confirmed optimal SMA placement mitigates residual drifts under horizontal and vertical seismic excitations. Abulfath [8] highlighted that SMA-equipped frames provide enhanced lateral stiffness, energy dissipation, and ductility, though base shear demands may increase. Across beams, frames, walls, and truss systems, the literature consistently shows that SMA reinforcement enhances energy dissipation, self-centering, and seismic resilience. However, most prior studies have focused on low- to mid-rise structures using simplified configurations, and only limited attention has been given to tall buildings and the influence of earthquake duration. Since long-duration ground motions exacerbate cumulative damage and residual drift, this remains a critical research gap. To address this, the present study investigates a 12-story RC special moment-resisting frame (SMRF) reinforced with SMA bars, focusing on collapse safety and residual drift control under both short- and long-duration earthquake excitations. Taken together, the literature confirms that SMA reinforcement can significantly improve energy dissipation, self-centering, and seismic resilience across beams, frames, and walls. However, the majority of prior research has focused on low- to mid-rise structures, often using simplified configurations, and has paid little attention to the role of earthquake duration in tall buildings. Long-duration ground motions, in particular, can exacerbate damage accumulation in higher-rise frames, a factor that remains largely underexplored. To address this gap, the present study investigates a 12-story RC special moment-resisting frame (SMRF) reinforced with SMA bars, focusing on collapse safety and residual drift control under short- and long-duration earthquake excitations.

2. METHODOLOGY

2.1. Building Layout and Design

Numerical modeling of concrete members for analyzing their response under loading is a common approach [20]. The case study structure is a 12-story reinforced concrete building with a combined lateral load-resisting system composed of a special moment-resisting frame and shear walls, enhanced with Shape Memory Alloy (SMA)

reinforcement. The building footprint is 20 m × 20 m with 5 m spans in both directions, and each story has a height of 3 m. The dimensions of the structural members are constant along the height: columns 70 × 70 cm, beams 55 × 55 cm, and shear walls 300 × 55 cm (Figure 1).

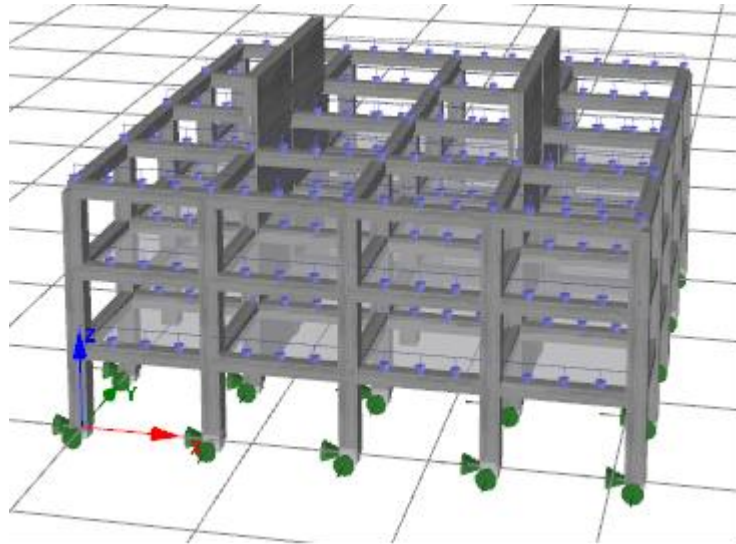


Figure 1. Building plan layout

2.2. Material Properties

The lateral resistance of the structure is provided by the interaction of the moment-resisting frame and reinforced concrete shear walls, designed according to ASCE 41-17. The properties of the materials employed in the structural design and analyses, including the concrete and steel used in beams and columns, are presented in Table 1. The compressive strength of concrete was taken as 35 MPa, and the yield strength of reinforcing steel was 400 MPa. Superimposed dead and live loads were

assumed as 3.5 kN/m² and 1.5 kN/m², respectively. Figures 2 (a–c) illustrate the cross-sections of the columns, beams, and shear walls. To investigate the potential of advanced materials, three types of SMA reinforcement were considered: NiTi (SMA1), Fe-Ni-Co-Al-Ti-B (SMA2), and Cu-Al-Mn (SMA3). These alloys were selected because of their distinct mechanical characteristics, including superelasticity and energy dissipation capacity. The material specifications are summarized in Figure 3.

Table 1. Material Properties Used in Structural Modeling

Material	Poisson's Ratio	Elastic Modulus (MPa)	Compressive Strength (MPa)	Unit Weight (kg/m ³)	Yield Stress (MPa)
Concrete	0.2	27.8×10^4	35	2400	-
Steel	0.3	2.00×10^5	-	7850	400

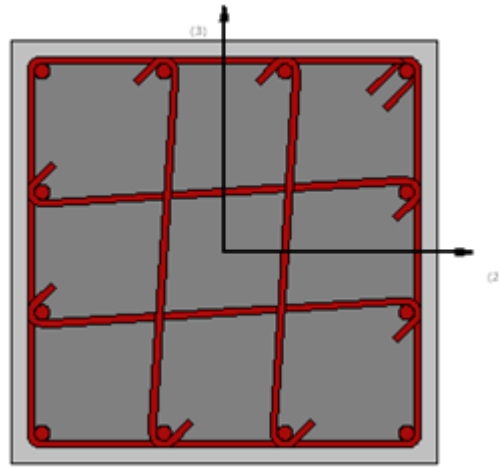


Figure 2(a). Column cross-section consisting of 12 longitudinal reinforcement bars with a diameter of 25 mm, transverse reinforcement (stirrups) with a diameter of 12 mm, along with 4 hooks spaced at 10 cm intervals.

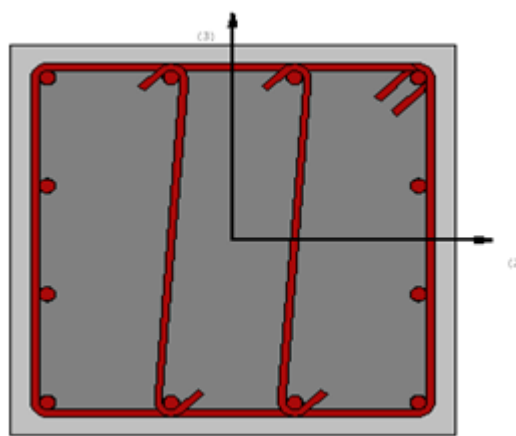


Figure 2(b). Beam cross-section consisting of 12 longitudinal reinforcement bars with a diameter of 20 mm, transverse reinforcement (stirrups) with a diameter of 10 mm, along with 2 hooks spaced at 10 cm intervals.

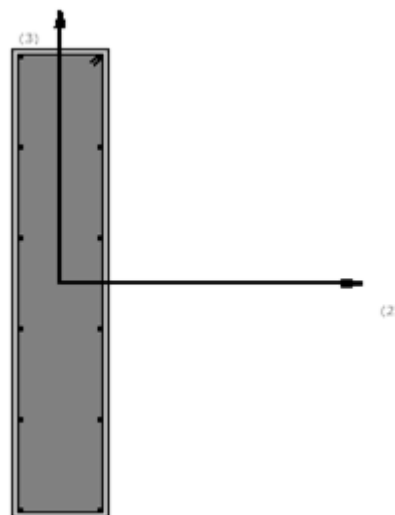


Figure 2(c): Cross-section of the shear walls consisting of 12 longitudinal reinforcement bars with a diameter of 20 mm, and transverse reinforcement (stirrups) with a diameter of 10 mm spaced at 10 cm intervals.

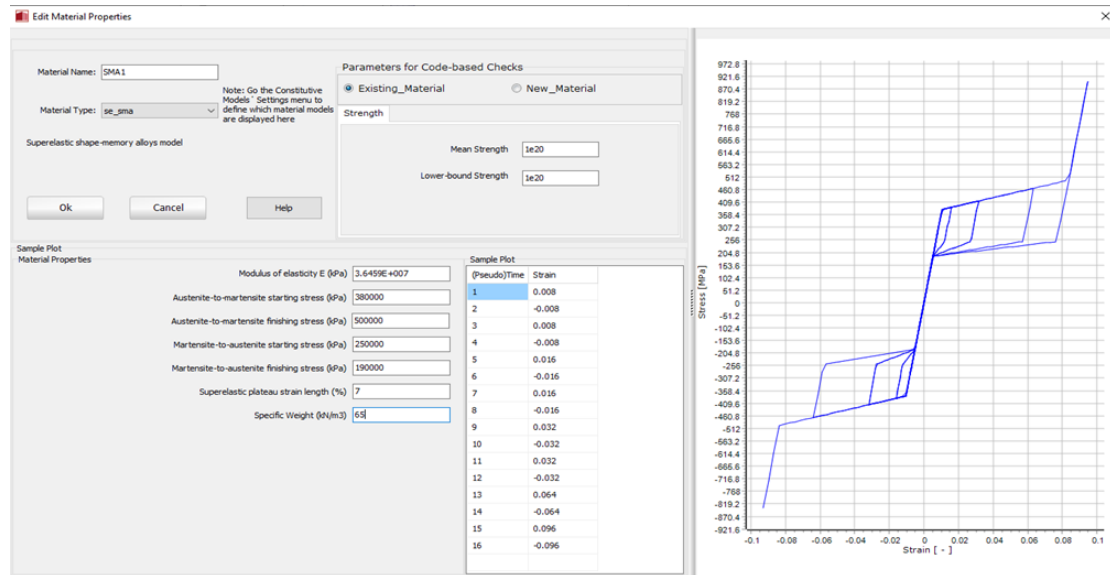


Figure 3(a). Specifications of the first type of Shape Memory Alloy reinforcement (SMA1)

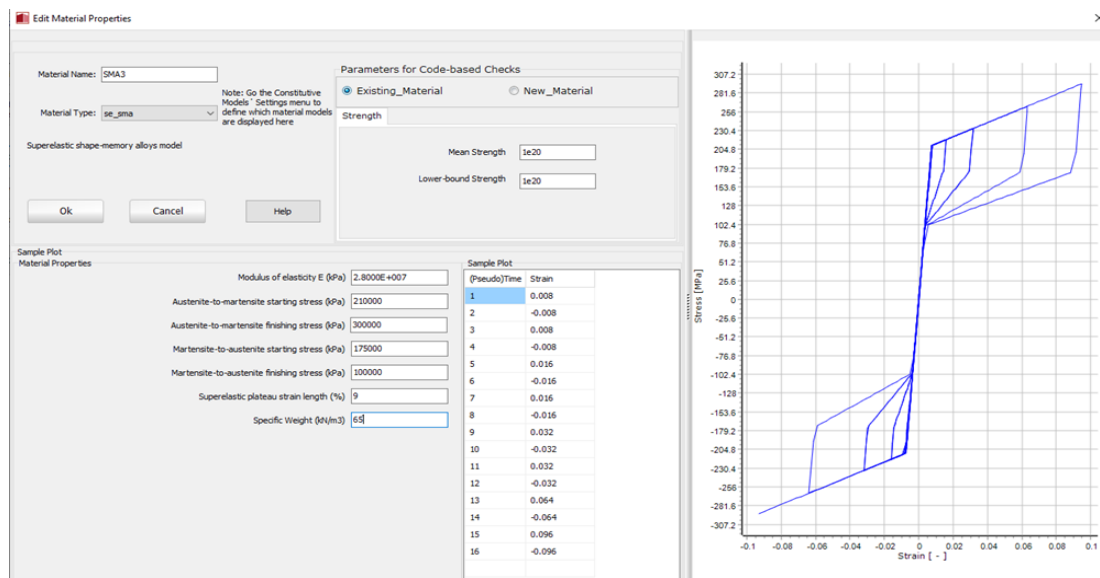


Figure 3(b). Specifications of the second type of Shape Memory Alloy reinforcement (SMA2)

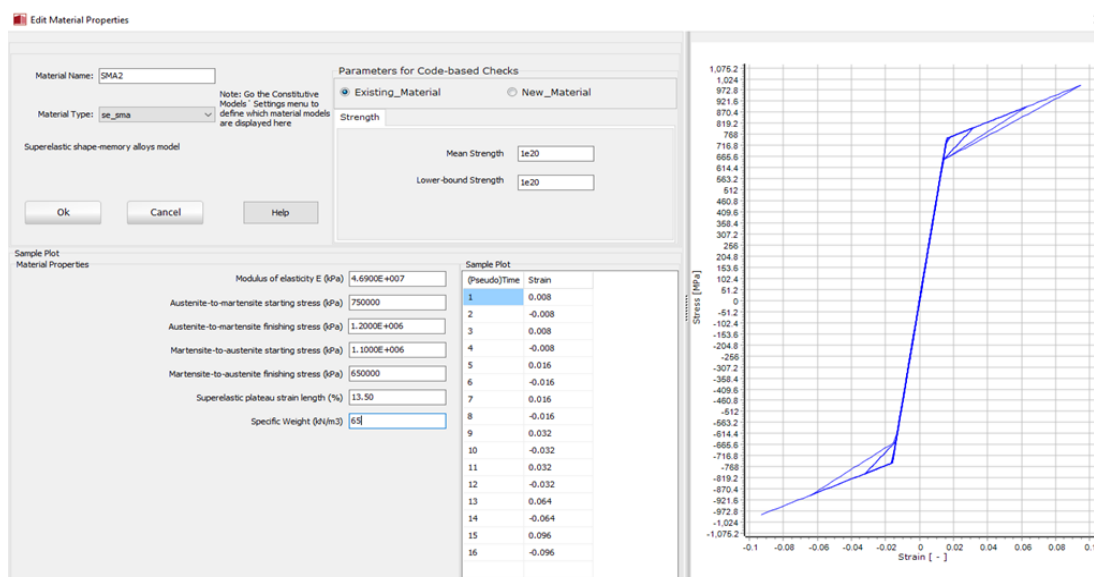


Figure 3(c). Specifications of the third type of Shape Memory Alloy reinforcement (SMA3)

2.3. Ground Motion Selection

Dynamic analyses were performed using nonlinear time-history simulations. The Hollister earthquake record ([Figure 4](#)), representing a long-duration input motion, was selected as the primary excitation. While only one record was used in this study to provide preliminary insights into SMA

2.4. Numerical Modeling

Numerical simulations were conducted in SeismoStruct, where beam-column members were modeled using fiber-based cross-sections to capture the nonlinear response of both concrete and reinforcement. A discretization scheme of 150×5 fibers was adopted.

SMA constitutive behavior was modeled using the built-in flag-shaped superelastic law. The adopted constitutive parameters—elastic modulus (EEE), forward transformation stress (f_{tr}), ultimate strain (ϵ_L), and residual strain recovery ratio—were calibrated based on the work of Abraik and Youssef [\[8\]](#), validated by Tolou Kian and Cruz-Noguez [\[9\]](#), and further supported by Alam et al. [\[2\]](#) and De Almeida et al. [\[7\]](#). The

performance, the limitation of single-record analysis is acknowledged. Future work will incorporate a suite of short- and long-duration motions to ensure statistical reliability and broader generalization.

model assumes stable superelastic response under cyclic loading, neglecting rate-dependency and low-cycle fatigue degradation, consistent with prior numerical studies. The specific parameter values for NiTi, Fe–Ni–Co–Al–Ti–B, and Cu–Al–Mn SMA alloys are summarized in [Table 2](#).

The numerical model and the distribution of shear walls are illustrated in [Figure 5](#). The interstory drift ratios obtained from the dynamic analysis are presented in [Table 3](#), comparing the seismic response of the SMA-reinforced and conventional RC cases. Negative drift values correspond to displacement direction and are reported as absolute values for clarity.

Table 2. SE-SMA bars parameters used in the numerical model

Alloy	Material	Parameter	Value
SMA1	Niti SE-SMA (55.9% Nickel and 44.1% Titanium)	Austenite yield strength, f_{y-SMA} (MPa)	380
		Austenite modulus, k_1 (MPa)	36.5
		Postyield stiffness, k_2 (MPa)	1724
		Recoverable strain, l_r	7%
		Lower plateau stress factor, β	0.55
SMA2	FeNCATB (59%-28%-17%-11.5%-2.25%-0.05%)	Austenite yield strength, f_{y-SMA} (MPa)	750
		Austenite modulus, k_1 (MPa)	46.9
		Postyield stiffness, k_2 (MPa)	3782
		Recoverable strain, l_r	13.5%
		Lower plateau stress factor, β	0.25
SMA3	CuAlMn (71.6%-16.1%-9.3%)	Austenite yield strength, f_{y-SMA} (MPa)	210
		Austenite modulus, k_1 (MPa)	28
		Postyield stiffness, k_2 (MPa)	788
		Recoverable strain, l_r	9%
		Lower plateau stress factor, β	0.7

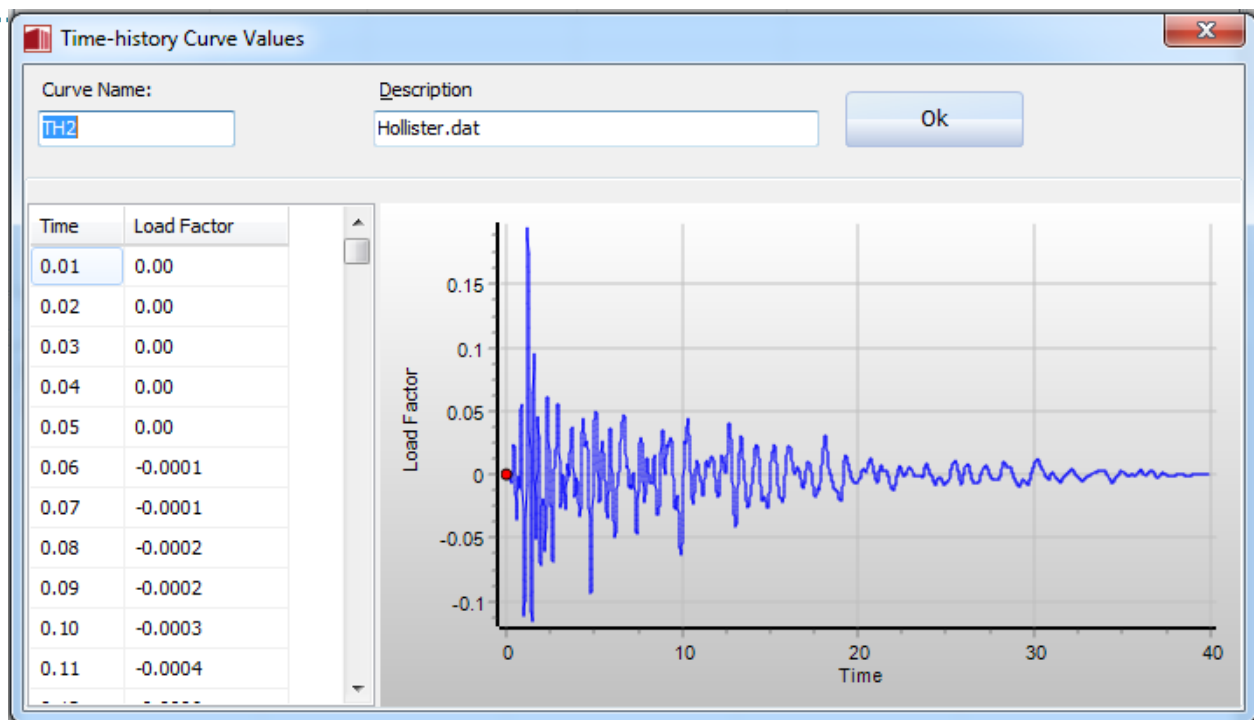


Figure 4. Hollister earthquake ground motion record

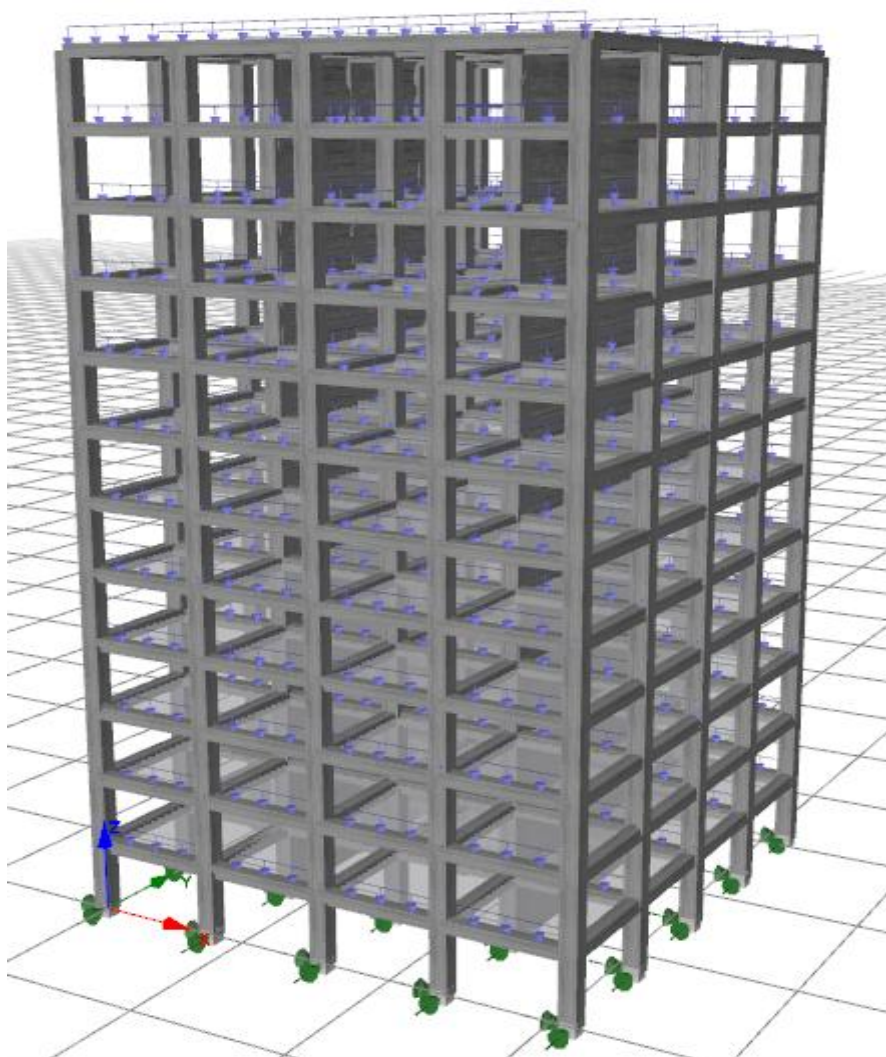


Figure 5. Three-dimensional numerical model of the 12-story RC-SMA building, including the distribution of shear walls along the plan.

3. RESULTS AND DISCUSSION

The analysis results indicate that the incorporation of SMA reinforcement significantly influences the seismic performance of the structure compared to the case without SMA. For the No-SMA model, peak interstory drift values are relatively high across stories, though residual drifts gradually decrease toward the upper stories. With the introduction of SMA reinforcement (SMA1–SMA3), both peak and residual interstory drifts are reduced, particularly in the upper levels, demonstrating improved self-centering capability

and reduced permanent deformations. Additionally, while the base shear and support moments vary slightly among the different SMA types, the overall structural weight remains nearly constant, suggesting that the observed improvements are primarily due to the mechanical contribution of SMA rather than mass effects. Among the SMA variants, SMA2 shows the most balanced response in terms of controlling both peak and residual drifts, indicating its effectiveness in enhancing seismic resilience.

Table 3. Interstory Drift Ratios of Stories for Reinforced and Non-Reinforced Cases with Shape Memory Alloy (SMA)

SMA reinforcement type	Structural Weight (kN)	Support Moment (kN·m)	Base Shear (kN)	Story	Residual Interstory Drift	peak interstory drift
No SMA	62335.07	19526.51	8192.6	1	0.003	0.006
				2	0.004	0.009
				3	0.004	0.009
				4	0.004	0.008
				5	0.003	0.009
				6	0.002	0.009
				7	0.002	0.008
				8	0.002	0.008
				9	0.001	0.009
				10	0.001	0.009
				11	0.001	0.007
				12	0.001	0.005
SMA1	62255.02	17171.00	8631.35	1	0.003	0.006
				2	0.005	0.008
				3	0.005	0.007
				4	0.005	0.007
				5	0.005	0.006
				6	0.005	0.006
				7	0.004	0.006
				8	0.003	0.006
				9	0.002	0.006
				10	0.002	0.006
				11	0.002	0.005
				12	0.001	0.004
SMA2	62255.02	18178.81	9352.83	1	0.003	0.007
				2	0.004	0.008
				3	0.005	0.007
				4	0.005	0.007
				5	0.006	0.006
				6	0.005	0.006
				7	0.005	0.006
				8	0.003	0.006
				9	0.002	0.007
				10	0.002	0.007
				11	0.002	0.006
				12	0.002	0.004
SMA3	62255.02	17242.69	8591.71	1	0.004	0.007
				2	0.007	0.009
				3	0.007	0.009
				4	0.006	0.009
				5	0.005	0.009
				6	0.004	0.009
				7	0.003	0.009
				8	0.003	0.009
				9	0.003	0.009
				10	0.003	0.011
				11	0.002	0.012
				12	0.001	0.006

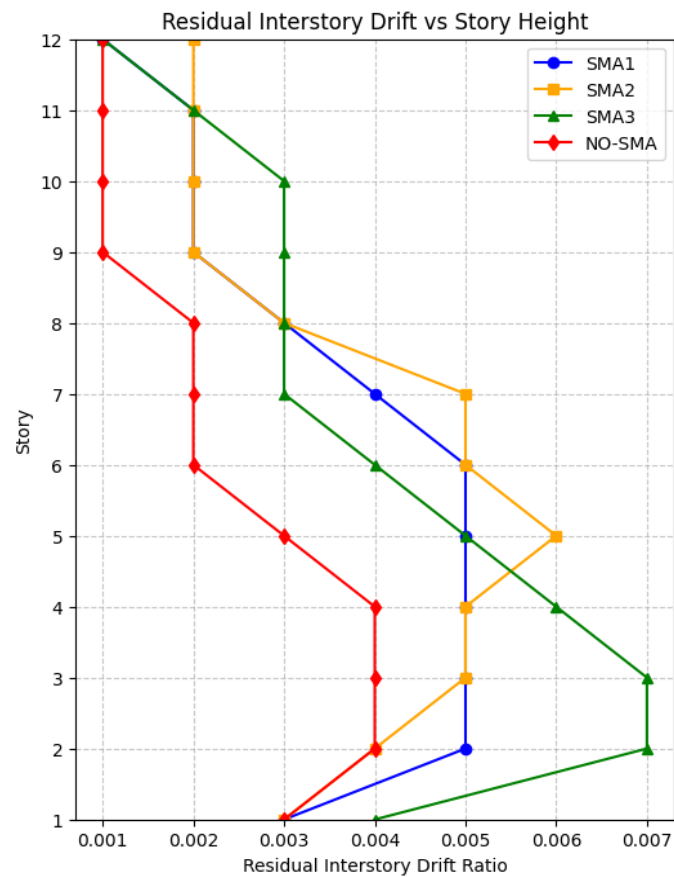


Figure 6. Peak interstory Drift vs.Story Height.

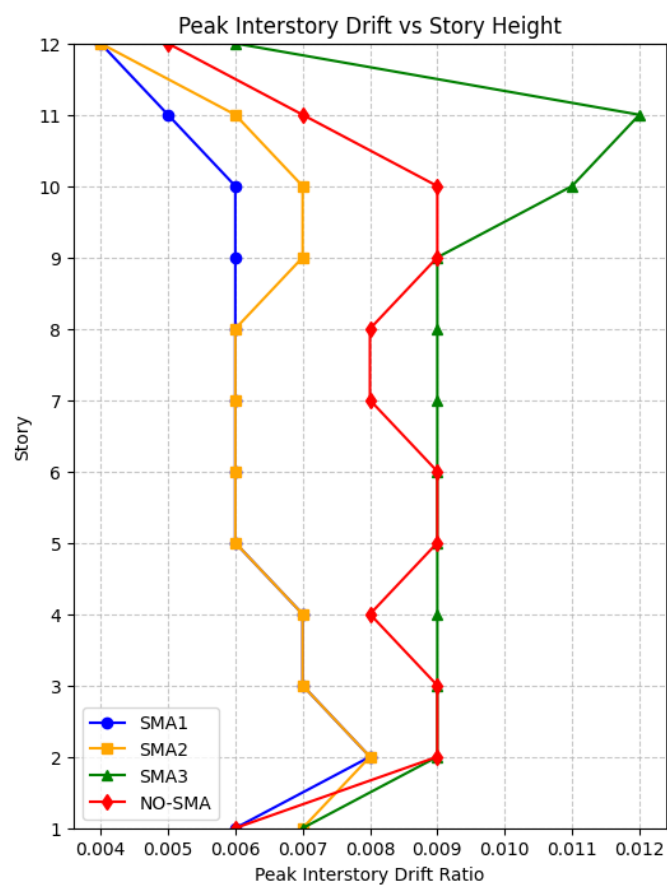


Figure 7. Residual interstory Drift vs.Story Height.

Figures 6 and 7 illustrate the variation of peak and residual interstory drift ratios along the building height for different SMA reinforcement types. The results confirm that SMA reinforcement significantly improves drift control compared to conventional RC.

Among the alloys, NiTi-SMA (SMA1) reduced peak drifts most effectively, demonstrating its superior contribution to seismic resilience. Fe-SMA (SMA2) provided a balanced improvement in both peak and residual drifts, owing to its higher yield strength and recoverable strain capacity. CuAlMn-SMA (SMA3) showed moderate performance, with smaller improvements in drift reduction, which can be attributed to its lower transformation stress and energy dissipation capacity compared to NiTi and Fe-based alloys. These findings indicate that material selection has a direct impact on seismic performance and should be design-specific rather than generic. It was also observed that, relative to the immediately lower story, both peak and residual interstory drifts decrease with increasing story

height. This behavior indicates that the combined stiffness of the SMA-reinforced moment-resisting frames and shear walls effectively controls lateral displacements in upper stories, thereby enhancing the overall seismic performance of the building. These trends are clearly visible in Figures 6 and 7, highlighting the important role of SMA reinforcement in mitigating interstory drifts, particularly in higher stories. To improve clarity, negative drift values reported in the raw tables were converted to absolute values, as they represent only the displacement direction rather than structural instability. The results demonstrate that SMA reinforcement not only reduces lateral deformations but also enhances post-earthquake functionality by limiting residual drifts. Overall, the graphical presentation provides a clear understanding of how different SMA alloys influence drift distribution along the building height. These insights can guide designers in selecting the most suitable SMA type for specific structural configurations and performance objectives.

4. CONCLUSION

This study evaluated the seismic performance of a 12-story RC building reinforced with different SMA types. The results demonstrated that SMA bars effectively reduce peak interstory drifts (up to 10.5%), and base moments ($\approx 10\%$), thereby enhancing seismic resilience throughout the building height. It was also observed that, relative to the immediately lower story, both peak and residual drifts decrease in upper stories, highlighting the efficiency of SMA reinforcement in controlling lateral displacements across all levels.

- **Material comparison:** Fe-based SMA achieved the most consistent benefits due to its higher yield strength and recoverable strain. NiTi exhibited strong residual drift recovery but at higher cost, while CuAlMn showed moderate improvements. These results indicate that SMA selection should be design-specific, considering both

structural performance and economic feasibility.

- **Practical implications:** SMA reinforcement is particularly valuable in critical infrastructure (e.g., hospitals, bridges, emergency centers), where post-earthquake operability is crucial. Fe-based SMA offers a promising balance between performance and cost, and material selection should also consider building height and load-resisting system characteristics for optimal seismic performance.
- **Future work:** Large-scale experimental validation, life-cycle cost-benefit analysis, and further evaluation of temperature-dependent properties and low-cycle fatigue of SMA bars are necessary to confirm feasibility in real construction projects

FUNDING/SUPPORT	AUTHORS CONTRIBUTION
Not mentioned any Funding/Support by authors.	This work was carried out in collaboration among all authors.
ACKNOWLEDGMENT	CONFLICT OF INTEREST
Not mentioned by Authors.	The author (s) declared no potential conflicts of interests with respect to the authorship and/or publication of this paper.

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